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White Paper Series: Municipal Solid Waste Landfills – Advancements in Technology and Operating Practices

Improvements in Intermediate and Final Landfill Covers to Mitigate Emissions

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White Paper for Evaluating Revisions to the Municipal Solid Waste (MSW) Landfills New Source Performance Standards (NSPS) and Emission Guidelines (EG)

- This series of white papers examines ways to improve the NSPS/EG for MSW Landfills using new information and new technology to further control and reduce landfill gas (LFG) emissions.
- Topics include applicability (size of landfill), controls (emission rate and timing of controls), operating practices (cover practices, working face), waste composition (organic waste), and monitoring (technology).

Topic: Improvements in Intermediate and Final Landfill Covers to Mitigate Emissions

This white paper describes how improvements to intermediate and final landfill covers can mitigate LFG emissions. Improving intermediate and final landfill covers significantly mitigates LFG emissions by promoting methane oxidation and enhancing the efficiency of gas collection systems. The design and material choice for landfill covers could be optimized to create favorable conditions for methanotrophic bacteria, which play a crucial role in converting methane into carbon dioxide, a less potent greenhouse gas. These optimized conditions include adequate oxygen supply, controlled moisture levels, and nutrient availability, all of which are essential for bacterial activity. Additionally, engineered covers are designed to allow better oxygen penetration into the waste, further facilitating the oxidation process. By transforming methane through biological means, improved covers act as an effective barrier to mitigate methane emissions.

Alongside oxidation, improved landfill covers are integral to boosting the performance of gas collection systems. These systems are meticulously integrated within the landfill cover, designed to capture methane more efficiently and direct it toward utilization or flaring systems. Enhanced covers prevent the escape of methane by minimizing gas migration and leaks, which can occur through imperfections in the cover, and also reduce the risk of air intrusion, which can dilute the collected gas and decrease its energy value.

In addition to direct effects on LFG emissions, landfill cover types determine the degree of infiltration of precipitation into the landfill. In wet climates, high precipitation can infiltrate the cover and saturate waste, resulting in accelerated gas generation and flooded collection systems, in addition to breakouts of leachate comingling with stormwater and creating other water quality concerns. Heavy rains can also damage soil covers and make them less effective in gas control.

Rationale and Possible Results

Types of Covers

The different types of landfill covers—daily, intermediate, and final—are crucial for the effective management of a landfill. Here is a summary and function of each type of cover:

Daily Cover: Daily cover is applied at the end of each day on the active fill area of the landfill. Its main function is to minimize odor, control vector access (such as pests), and reduce windblown litter. Materials for daily cover include soil, synthetic material tarps, shredded brush materials, spray-on foam products, and more. The typical thickness is around 15 centimeters (cm) (or 6 inches) when soil is used, but alternative daily covers are often only a few millimeters (mm) for tarps or <1 cm for foams.

Intermediate Cover: Intermediate cover is used on sections of the landfill where waste has been deposited but the section will not be active for more than 180 days. The intermediate cover is generally thicker than daily cover (around 30 cm). If designed well, intermediate cover serves to prevent erosion, promote evapotranspiration through planted vegetation, control gas migration by resisting emissions into the atmosphere, help gas collection systems, and provide methane oxidation conditions. The material used is often the available native soil at the landfill. At some landfills, exposed geomembranes are paired with soils to provide better gas control and/or liquids management.

Bare soils, particularly 30 cm or less, can be very vulnerable to damage from rain events, resulting in erosion and a thinner, less protective cover. Exposed waste can be a common result of cover damage, resulting in paths for LFG release.

Final Cover: Applied to areas that have reached full capacity, the final cover system is designed to seal the landfill to minimize water infiltration and enhance gas collection efficiency. This cover system typically includes multiple layers:

- A topsoil layer to support vegetation (15 cm thick)
- A protective soil layer (about 60 cm thick)
- A drainage layer (20-30 cm of coarse material)
- A barrier layer of clay with low hydraulic conductivity (60 cm thick), possibly with a geomembrane
- A grading layer to provide a uniform surface for barrier placement (15-60 cm thick).

The problems with daily covers and working face areas are discussed in a separate paper. This paper discusses emission mitigation strategies for intermediate and final covers. Each type of cover has specific functions geared toward environmental protection and operational efficiency of the landfill. The choice of materials and their arrangement in the intermediate and final cover systems play a significant role in reducing landfill emissions by enhancing methane oxidation or collecting more LFG.

Methane Oxidation

Methane oxidation in landfills is a critical environmental process that mitigates the release of methane into the atmosphere. This process occurs in the top layers of waste or in the soil cover of the landfill, where conditions favor the activity of methane-oxidizing bacteria (methanotrophs).

Methane oxidation in landfills occurs when methanotrophic bacteria utilize methane as a carbon and energy source. These bacteria are present in the soil or waste cover material and require oxygen to metabolize methane, converting it into carbon dioxide and water:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

This process effectively reduces the global warming impact of landfill emissions, as carbon dioxide is less potent as a greenhouse gas compared to methane.

Several factors influence the efficiency of methane oxidation in landfills:

- Oxygen Availability: Oxygen is a critical component for the methane oxidation process. Its availability can be influenced by the porosity and compaction of the cover material, atmospheric pressure changes, and the presence of plants that can transport oxygen to their root zones.

- Temperature and Moisture: Methanotrophic bacteria thrive within certain temperature and moisture ranges. Extreme temperatures and either too much or too little moisture can inhibit their activity.
- Soil or Cover Material: The type of material covering the landfill can affect methane oxidation. Materials that support good air and moisture movement and provide necessary nutrients can enhance methanotrophic activity.
- Methane Concentration: High concentrations of methane can inhibit methanotrophic bacteria, while too low concentrations may not provide enough substrate for their growth.

Enhancing methane oxidation in landfills involves optimizing these factors, often through the engineered design of landfill covers, including biocovers specifically designed to maximize methanotrophic activity.

Gas Collection Efficiency

Improving the cover of a landfill can significantly increase gas collection efficiency through several mechanisms. A well-designed cover minimizes gas migration and leakage. Gas can escape through imperfections or weak spots in the cover, but an improved cover is constructed to be more uniform and less permeable to gas, except where intentional gas collection points are established. This containment leads to a higher concentration of gas being directed toward the collection points. Finally, advanced cover systems may include passive or active venting mechanisms that help regulate the pressure within the landfill, encouraging gas to flow toward the collection points. By managing the internal dynamics of the landfill, these systems ensure that methane is not only generated but also efficiently captured and transported out of the landfill for flaring or energy recovery. This comprehensive approach to cover design and LFG management significantly enhances the overall efficiency of gas collection systems.

Moreover, improved covers can be engineered to minimize air intrusion, which is crucial because the introduction of too much air can dilute the methane concentration in the collected gas, reducing its quality and energy value. A carefully designed cover can balance the need for oxygen to promote methane oxidation in the upper layers while preventing excessive air from mixing with the methane being collected for energy use.

Investigations

Effects of Climate on Methane Oxidation

The detailed investigation by Chanton et al. (2011) utilized stable isotope analysis over a span of four years at 20 landfill sites equipped with intermediate or final covers to thoroughly assess the effectiveness of methane oxidation under varying seasonal conditions. This study, which took into account 37 different sampling events across various seasons, provided a deeper understanding of how methane oxidation rates are influenced by changing environmental factors and the unique characteristics of each landfill site. The innovative use of isotopic signatures to trace methane transformations not only shed light on the dynamic interactions affecting methane oxidation in landfill covers but also played a pivotal role in enhancing the knowledge base necessary for optimizing landfill management strategies aimed at minimizing the release of greenhouse gases. Figure 1 illustrates the methane oxidation rate versus the methane loading to the bottom of the landfill cover as a result of this study.

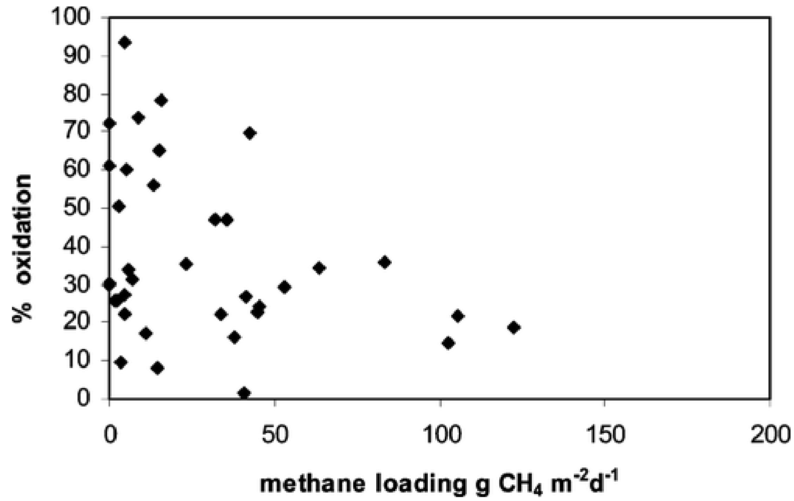

Figure 1. Methane oxidation versus methane loading to the bottom of the landfill cover (Chanton et al., 2011).

Intermediate Covers

An improvement in LFG collection systems, detailed by Augenstein and colleagues in their 2007 patent, aims to enhance LFG capture, prevent air from entering the landfill, and decrease the escape of methane. This system, depicted in Figure 2, incorporates a gas-permeable conductive layer situated close to the landfill surface, specifically designed for use in landfills with intermediate covers that might stay in place for extended periods before further waste is added. The key feature of this high-permeability layer is to balance the gas pressures underneath the landfill cover. Unlike traditional methods, gases are extracted not from this layer but from deeper within the refuse through wells. This design is intended to offset limitations that reduce the effectiveness of traditional gas extraction wells.

Jung et al. (2009) compared its performance with that of traditional gas collection methods. The study involved modeling LFG movement and examining alternative methods by analyzing how the high-permeability layer impacts the efficiency of gas collection and the extent of oxygen intrusion under various landfill conditions, including changes in barometric pressure, waste permeability variations with depth, waste anisotropic permeability, and the positioning of the permeable layer within the landfill. Simulations suggested that this new system could substantially reduce methane leakage and improve the quality of the LFG collected.

Traditional active gas collection systems typically use a vacuum to draw gas from the waste through either vertical wells or horizontal trenches. These conventional systems can lead to uneven methane emissions and air entering the landfill at the surface. In contrast, the design proposed by Augenstein et al. (2007) features a high-permeability layer near the surface, with LFG collected from deeper wells, and is expected to result in more efficient gas collection by equalizing gas pressure variations near the surface. This approach could lead to lower methane emissions from the cover materials, more uniform LFG flow, and reduced air intrusion.

Historically, permeable layers have been incorporated in landfill designs as venting layers within the final cover system to release LFG from decomposing waste below. Sometimes, these surface permeable layers are used alongside a vacuum system to actively pull gas, but usually, LFG movement through these layers happens passively due to natural pressure gradients within the closed landfill.

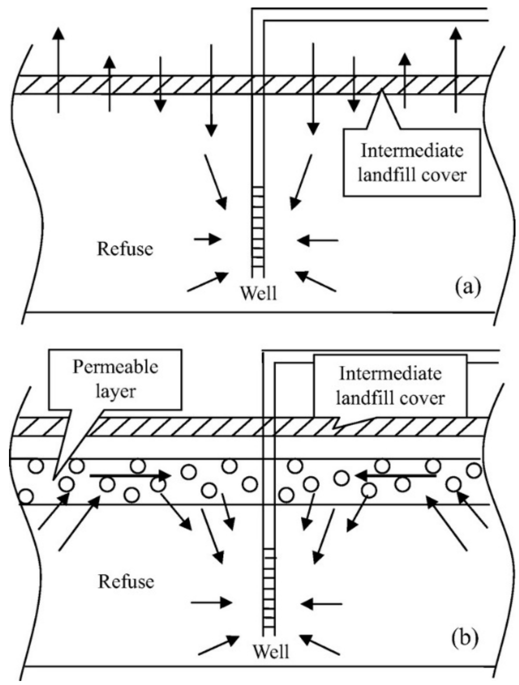

Figure 2. Cross section of a) conventional gas collection systems, b) gas collection systems with high permeable layer (Jung et al., 2009).

Final Covers

Regarding final covers and the decommissioning of gas collection systems, the economic feasibility of LFG utilization systems tends to wane in aging landfills, where methane levels generally decrease over time. This decrease presents challenges in managing the diluted LFG that might escape and create environmental risks. To address this issue, strategies such as the use of extraction wells to release low-methane, high-oxygen gas from the soil have been investigated. Studies by Haubrichs and Widmann (2006) and Farrokhzadeh et al. (2017) have explored the efficiency of biofilters in treating LFG with a methane concentration of about 30 percent by blending it with atmospheric air at various stages. These studies demonstrated high efficiency in methane removal. Additionally, Thomasen et al. (2019) simulated a pilot-scale biocover, which successfully treated LFG containing low methane levels (3 percent to 12 percent methane) by incorporating oxygen, although it did not reach its maximum oxidation potential. These findings highlight the critical need to thoroughly understand the methane oxidation capabilities of biofilter systems to optimize their design, particularly in determining the ideal size of the methane oxidation layer.

The literature on enhancing intermediate and final landfill covers for emission reduction primarily focuses on two strategies: selecting optimal materials and designing effective structural schemes. Material choice revolves around properties like permeability and oxidative capacity to facilitate gas movement and methane breakdown, emphasizing sustainable and durable materials like biochar and compost. Structural design considerations highlight a layered approach, integrating efficient gas collection systems beneath bioactive layers for methane oxidation. This dual focus aims to improve LFG management, reduce emissions, and enhance environmental sustainability through carefully chosen materials and strategic cover configurations.

Results

Utilizing Organic Cover Materials to Enhance Methane Oxidation

The study by Mei et al. (2015) explores the efficacy of using yard waste as a biocover material for methane oxidation in landfill covers. This research focuses on understanding how different stages of green waste maturity—specifically, "fresh" green waste aged 2 months and "aged" green waste aged 24 months—perform under high LFG loading conditions. Over a 15-month testing period in biocover test cells, both types of green waste demonstrated promising initial oxidation rates of methane, achieving 200 grams per meter squared per day (g/m²/day) for fresh green waste and 140 g/m²/day for aged green waste. These findings are significant as they indicate that green waste, a less costly alternative to traditional green waste compost, can meet the respiration requirements for landfill compost covers while effectively oxidizing methane.

However, the study also highlights several challenges associated with green waste biocovers. Seasonal variations, particularly during colder months, led to a decrease in methane oxidation rates and an increase in methane production from anaerobic zones within the 60-80 cm thick biocovers. This finding suggests that while green waste has potential as a biocover material, its performance can be hindered by temperature fluctuations and the stability of organic matter. The research points out the necessity of considering the moisture and temperature dependency of methane oxidation when employing green waste, as these factors can significantly influence the efficacy of biocovers.

Moreover, the study raises questions about the long-term stability and viability of green waste as a biocover material, given the observed methane generation during the second year of operation and the significant spatial variability in moisture within the biocovers. These findings underscore the need for further research and development of biocover materials and designs that can address these challenges, ensuring effective and sustainable methane mitigation from landfills. The study emphasizes the crucial roles that bed material and oxygen availability play in the efficiency of biomitigation systems for landfill methane emissions. Compost, commonly used as a landfill cover material for methane removal, can paradoxically compete for oxygen with methanotrophic bacteria and contribute to carbon dioxide emissions, highlighting the need for alternative materials that can sustainably support methane oxidation without depleting oxygen levels or contributing significantly to carbon dioxide emissions.

Huang et al. (2020) pointed to the potential of biochar as an innovative amendment to landfill cover systems. The introduction of biochar to landfill cover soil not only improves soil properties but also promotes the growth of methane-oxidizing bacteria. This study found significant increases in methane removal efficiencies with biochar amendment—up to 85.2 percent for biochar-amended landfill cover and even higher, at 90.6 percent, when the biochar-amended landfill cover was also aerated. These findings suggest that biochar can enhance the aeration of the soil, possibly through its porous structure, which facilitates the diffusion of oxygen deeper into the soil layers where methane oxidation occurs.

These results underscore the importance of selecting appropriate materials for landfill covers and the potential benefits of active aeration strategies to enhance methane oxidation. The ability of biochar to improve soil structure and oxygen penetration, along with its capacity to support microbial growth, makes it a promising addition to biomitigation strategies for landfill methane emissions.

Advantages and Disadvantages of Biocovers

Biocovers are designed as part of landfill infrastructure to tackle methane emissions, utilizing large areas of the landfill cover to oxidize methane, thereby reducing emissions if some gases are escaping from gas extraction systems. Biocovers are crucial to the landfill overall design and also fulfill general functions of the final soil cover like recultivation and water balance management. These covers need to perform various roles, including acting as a recultivation layer, managing water, and meeting geotechnical standards for future landfill use. Therefore, the materials used must have good water retention and gas movement properties. The need for large volumes of suitable materials can lead to significant costs and availability issues.

Biocovers have the advantage of covering large areas, reducing the methane concentration per area. However, this comes with the challenge of evenly spreading methane, especially when the exact escape points of LFG and their overall contribution are unclear. Managing moisture is also tricky, as even distribution is necessary to avoid moisture buildup at the GDL-MOL interface, particularly on slopes. Techniques like adding drainage spots or designing a sloped interface can help, along with choosing substrates and building methods that account for higher methane concentrations in higher areas to increase oxidation capacity.

One main issue facing biocovers is that high levels of LFG can limit oxygen diffusion into the cover material, which is crucial for the methane-consuming bacteria. During design, it is important to consider the media diffusivity and expected LFG levels to ensure enough oxygen gets through for effective methane oxidation. Temperature changes, especially in colder months, can affect biocover efficiency since the bacterial activity, necessary for methane breakdown, decreases at lower temperatures, leading to less effective methane control in winter. The risk of the biocover material drying out due to fluctuating wet and dry conditions is another concern. Choosing materials with good water holding capacity can help maintain moisture levels suitable for microbial life.

Using organic materials in biocovers also brings the possibility of self-degradation, which can ironically lead to methane production, undermining the intended methane reduction. Excessive production of microbial byproducts under high oxygen conditions can block the material pores, preventing oxygen from reaching deeper layers for methane oxidation. Compost-based materials, often used in biocovers, face additional hurdles. Compost-based materials might not effectively adsorb methane and could inhibit bacterial activity due to excess nutrients. The compost maturity is crucial, as immature compost can produce significant greenhouse gases during composting itself. The seasonal availability of compost also limits the broader use of biocover systems, making them a less appealing option for landfill operators who need year-round solutions.

Microbial Methane Oxidation Systems

The anticipated rise in emissions linked to increasing waste generation, especially in regions where landfilling of biodegradable wastes remains prevalent, underscores the urgent need for innovative mitigation technologies. Microbial methane oxidation systems (MMOS) have gained recognition as a viable solution, offering a particularly effective approach for managing emissions from sites where conventional gas extraction methods may fall short including older landfills or those characterized by low gas production potential.

MMOS are designed with multiple key layers, each crafted to perform a specific role that collectively enhances the overall efficiency of the system (Gebert et al., 2022). As shown in Figure 3, these layers include a gas distribution layer (GDL), which ensures the even spread of LFG throughout the system; a methane oxidation layer (MOL), densely populated by methanotrophic bacteria that consume methane as their primary energy and carbon source, converting it to carbon dioxide; a moisture retention layer, which maintains optimal moisture levels crucial for bacterial activity; and a top cover layer, which serves to protect the system from external elements and to manage gas emissions effectively. By integrating these specialized layers, MMOS effectively harnesses the power of natural microbial processes to mitigate methane emissions, providing an eco-friendly solution to the challenges posed by LFG.

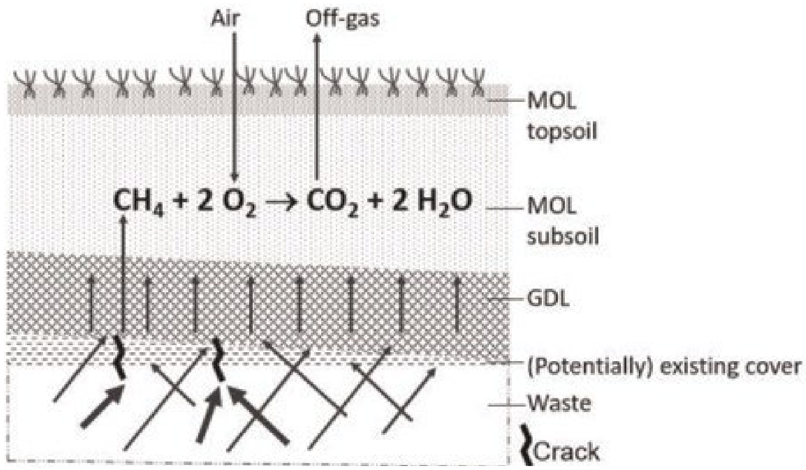

Figure 3. Scheme of microbial methane oxidation systems in biocovers (Gebert et al., 2022).

Microbial methane mitigation systems are made of multiple layers:

Base Layer: This layer forms the foundation of MMOS. For systems installed below ground, this base layer often means using the pre-existing landfill cover or a soil layer directly above the waste. In contrast, above-ground systems need a foundation that blocks gas from escaping and may use compacted non-reactive waste for this purpose.

Gas Distribution Layer: Essential for evenly spreading methane gas to the layer above, the GDL (coarse-grained materials) plays a key role in avoiding system strain and preventing areas of intense heat due to uneven gas distribution. It must be made from materials that are long-lasting, crack-resistant, and maintain their structure to ensure gas and water move through effectively, without reacting chemically in a way that might degrade its performance. As discussed earlier, Jung et al. (2009) showed how GDL can enhance gas collection efficiency in intermediate covers as well.

Intermediate Filtering Layer (IFL): Located between the GDL and the MOL, the IFL stops particles from moving upwards, which could block the system, and helps equalize water movement between the layers, preventing the methane conversion layer from becoming waterlogged and less effective. Commonly, the filter layer consists of gravel or crushed stone with particle sizes ranging from 10-20 mm, ensuring adequate permeability while blocking fine particles. Coarse sand can also be used as it offers a balance between filtration and gas flow. In some cases, geotextiles are incorporated to enhance separation between the GDL and MOL, while still allowing gas to flow through effectively.

Methane Oxidation Layer: At the heart of MMOS, the MOL is where methane is broken down by microbes. It is often filled with organic substances like compost to support the methane-eating bacteria.

The design considerations here include maintaining the right moisture level, ensuring air can move through, and fostering microbial activity to maximize methane breakdown.

In MMOS, including biocovers, the layering of materials can lead to varying textures and differences in unsaturated hydraulic conductivity, and may cause moisture to build up just above where finer and coarser materials meet, known as the *capillary barrier effect*, which can block gas movement. A capillary barrier is a system that uses the contrast in permeability between two layers of soil or materials to prevent water from moving between them. Typically, a fine-grained layer is placed above a coarse-grained layer, causing water to accumulate in the finer material due to its higher capillary forces. This prevents downward movement of water into the coarse layer until the upper layer becomes saturated. Capillary barriers are often used in landfills to limit the infiltration of water into waste layers, enhancing containment.

The challenge in designing MMOS is to balance water and gas movement, particularly in sloped systems where moisture at the MOL-GDL interface can stop gas flow. Solutions include careful design to balance gas movement types and strategic material placement and system design for effective gas and moisture management. Despite their benefits, MMOS can face challenges such as the influx of LFG reducing oxygen, which is crucial for the bacteria, and changes in temperature affecting how well the system works, especially in cooler months. The organic material in the MOL might also break down over time, leading to settling and decreased effectiveness. Additionally, the buildup of microbial byproducts can block the system, restricting oxygen flow and methane breakdown.

To overcome these hurdles, careful material choice and design are crucial. Innovations like adding biochar to the soil have shown potential in boosting methane breakdown by improving soil conditions and microbial life. Using green waste instead of traditional compost as a cover material might offer a cost-effective option, though its effectiveness can vary based on its condition and the landfill cover environment.

In sum, MMOS offer a promising method for reducing landfill methane emissions, but their design and deployment need to consider various factors including material choice, environmental conditions, and methane oxidation challenges specific to landfills.

Increasing Gas Collection Efficiencies in Intermediate Covers

While current regulations (the Resource Conservation and Recovery Act (RCRA), Subtitle D) mandate that intermediate covers be at least 12 inches thick, recent studies suggest potential improvements for emission mitigation. Specifically, Jung et al. (2011) demonstrated the benefits of incorporating a high-permeability layer near the top surface of landfills, such as a GDL. This modification can enhance the efficiency of gas extraction systems. By introducing a high-permeability layer, the rate of gas collection at extraction wells can be improved, thereby reducing the volume of methane emissions released into the atmosphere. This enhancement is directly linked to increased permeability within the refuse, which facilitates more efficient gas extraction.

The high-permeability layer hosts a larger porous volume and more expansive gas flow channels, facilitating a quicker migration of gases into the extraction wells. A pivotal factor in this process is the ratio of horizontal to vertical permeability within the landfill. An increase in this ratio amplifies the lateral flow velocity of LFG, leading to a substantial boost in LFG extraction efficiency. This phenomenon underscores the importance of strategic layer placement and material selection in landfill design to optimize gas collection and mitigate environmental impacts. Results from Jung et al. (2011) indicate that this permeable layer can counteract against lower barometric pressure that enhances methane emissions. As shown in Figure 4, the presence of this permeable layer mitigates methane emissions.

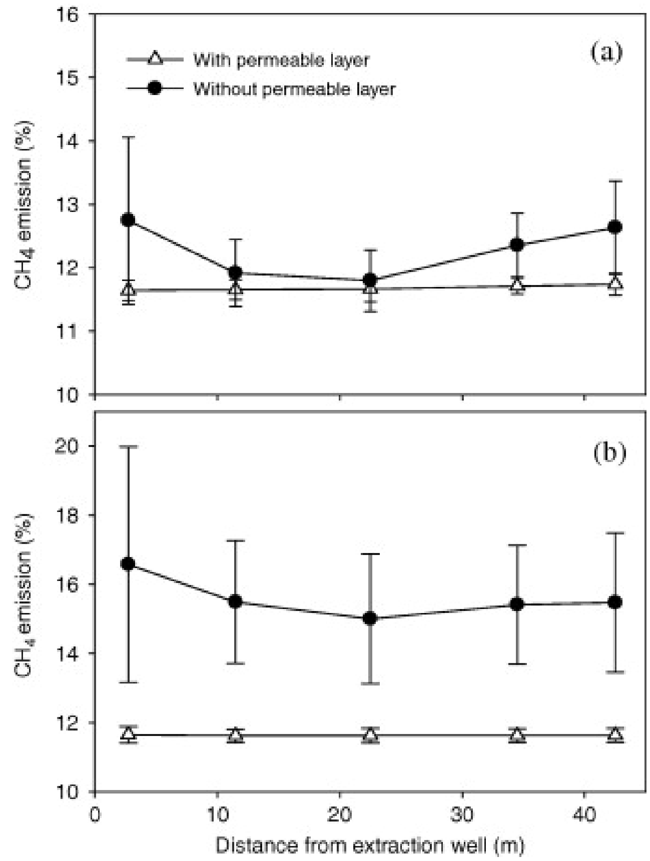

Figure 4. Changes in methane emissions after installation of horizontal permeable layer a) conventional soil permeability, b) 10 times higher permeability for both directions than conventional (Jung et al., 2011).

Alternative Final Cover Options for Landfills

The RCRA subtitle D federal standards set forth in 40 CFR part 258, subpart F, mandate that landfill operators implement a final cover system designed to minimize liquid infiltration and prevent soil erosion. The permeability of this final cover system must be lower than that of the bottom liner system, if one exists, or the natural subsoils beneath, and should never exceed 1.0×10^{-5} cm/s. According to the guidelines, the final cover must include at least 45cm (18 inches) of earthen material as an infiltration or barrier layer, topped by at least 15 cm (6 inches) of another earthen layer that facilitates vegetation growth, as depicted in Figure 5. Figure 5 illustrates the subtitle D cover system configuration for MSW landfills, both with and without geomembrane liners at the base.

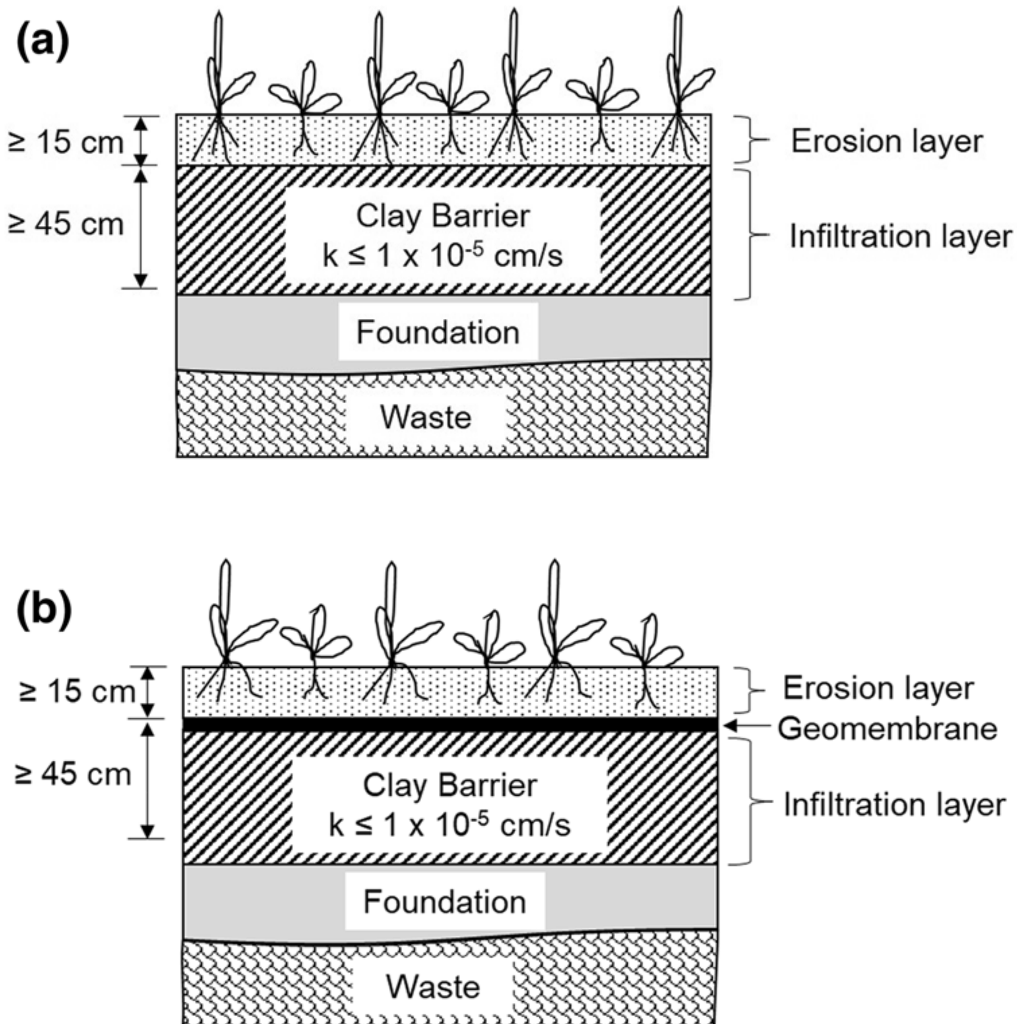

Figure 5. MSW landfill cover requirement by subtitle D for a) unlined landfills, b) lined landfills (Chetri and Reddy, 2021).

The topmost layer of a typical final cover, known as the vegetative or erosion layer, protects against erosion and supports plant growth if the local climate is conducive. Occasionally, nutrients might be added to enhance vegetation in the topsoil or vegetative layer. In regions prone to frost, an additional soil layer beneath the erosion layer may act as a protective layer to mitigate frost damage. This protective layer also helps to temporarily hold infiltrated water, which is later removed through evapotranspiration. In areas with significant rainfall, a drainage layer is included to reduce seepage through the barrier layer, lessen the hydraulic pressure on the liner from percolation, and prevent stability issues due to water pressure. For landfills expected to generate substantial methane, a gas collection layer is incorporated to facilitate the installation of gas vents.

Alternative final covers for landfills are designed to prevent the infiltration of water, control gas emissions, and support vegetation, all while being sustainable and cost-effective. Following are some of the innovative types of final covers used for landfills.

Capillary Barrier Systems:

A capillary barrier consists of a fine-grained soil layer underlain by a coarse-grained soil layer, functioning to inhibit water infiltration through capillary action. This design exploits the differential pore sizes between the layers—smaller pores in the fine-grained upper layer and larger pores in the coarse-grained bottom layer—to prevent water from permeating deeper into the landfill. The effectiveness of the capillary action hinges on the matric suction (the pressure difference between pore air and pore water in unsaturated soil, which influences the movement of water and soil strength) within the fine soil, which holds water until it reaches a saturation point, at which the larger pores of the underlying layer no longer support the capillary rise, allowing water to advance.

Capillary barriers effectively limit deep drainage until the fine soil layer is fully saturated. To enhance the efficiency of these covers, accumulated moisture in the fine-grained layer can be removed through evapotranspiration via the vegetative cover or by lateral transport in an inclined cover setup.

While capillary barriers are particularly suited to arid and semi-arid climates, their performance may be compromised in regions with heavy annual rainfall. An essential consideration in employing these systems is the potential occlusion of soil pores upon saturation, which can obstruct gas transport, leading to the accumulation of LFG beneath the barrier if not properly managed with gas wells or collection systems. One serious concern with capillary barrier systems can be the formation of cracks during wet and dry seasons that can be a preferential pathway for methane.

Evapotranspiration Cover:

Evapotranspiration cover systems, also known as water balance covers, vegetative landfill covers, or soil-plant covers, employ a thick soil layer with a vegetative cover that retains water until it naturally evaporates or is transpired by plants. This design strategically utilizes the site-specific hydrological processes, including the soil water storage capacity, precipitation patterns, surface runoff, and evapotranspiration rates. The goal is to minimize percolation through the cover by using materials that enhance water storage and evapotranspirative properties.

There are two primary types of evapotranspiration cover systems:

- Monolithic Barriers: These systems use a homogeneous, vegetated fine-grained soil layer to store water and prevent deep drainage, effectively managing the "bathtub effect."
- Capillary Barriers: As mentioned previously, which retains more water than a monolithic system of the same thickness because the coarse layer creates a capillary break, preventing further water movement downward.

Evapotranspiration cover systems are not universally applicable and are most suitable for arid or semi-arid regions, where their design can effectively manage local climatic conditions. These systems might require modifications to adequately control gas emissions, as LFG can be toxic to the vegetation used in evapotranspiration covers and might necessitate additional gas capture and venting mechanisms. While evapotranspiration covers offer significant advantages such as cost savings and aesthetic improvements over conventional covers, their effectiveness can vary based on vegetation maturity, local soil conditions, and extreme weather events. The design of evapotranspiration covers must therefore consider the growth period of vegetation and the potential for saturation during heavy precipitation events, which may compromise the cover functionality.

Geosynthetic Clay Liners:

Geosynthetic clay liners (GCLs) serve as an innovative alternative to traditional compacted clay liners in landfill cover systems. GCLs consist of a layer of bentonite clay, which is a highly absorbent material, sandwiched between textiles or bonded to geomembranes. GCLs offer a synthetic solution to the need for low-permeability barrier layers in landfill covers.

GCLs are particularly beneficial in regions where naturally occurring low-permeability clay is scarce. Their thinner profiles not only reduce material requirements but also decrease the spatial footprint of the landfill, thereby increasing its capacity. GCLs are known for their low hydraulic conductivity (approximately 10^{-9} cm/s), ease of installation, and resilience against environmental stressors like freeze-thaw cycles and wet-dry conditions. These properties make GCLs highly effective in minimizing leachate migration.

The primary component of GCLs, sodium bentonite, expands upon contact with water, filling the microscopic flow paths within the liner. This swelling property enhances the self-healing capabilities of GCLs, allowing them to seal punctures or tears autonomously. Sodium bentonite high ion exchange capacity and interlayer swelling contribute significantly to the overall impermeability of the liner.

Enhanced versions of GCLs that include components like needle-punched or stitch-bonded textiles provide additional shear strength, essential for maintaining the integrity of the landfill cover under various load conditions.

Extensive research and field applications have demonstrated that GCLs are reliable as landfill cover barriers. However, factors such as ion exchange, desiccation, and root penetration can affect their long-term hydraulic conductivity. For instance, exposure to cycles of wetting and drying can lead to an increase in the hydraulic conductivity of GCLs, as can the ion exchange from sodium to calcium or magnesium. This is often observed in environments not isolated from calcium-rich soils or leachate. GCL installations typically involve a sand drainage layer above and a protective soil layer on top to guard against mechanical damage and natural elements.

GCLs represent a technologically advanced option for landfill final covers, offering significant improvements in terms of installation efficiency, environmental protection, and operational longevity. However, their effective use requires detailed planning and consideration of site-specific factors to fully leverage their benefits while mitigating potential drawbacks.

Geomembrane Covers:

Geomembrane covers offer a specialized alternative to traditional cover systems in landfill applications. Geomembrane covers provide significant advantages and are configured to meet specific environmental and operational requirements.

Geomembrane covers are distinctive in that they do not incorporate the conventional drainage layers, topsoil, or erosion layers typically found in landfill cover systems. This absence is primarily due to their design purpose, which is to offer a quick and effective solution for landfill coverage that may not necessarily support vegetation. Geomembrane covers significantly decrease the amount of methane emissions as well as precipitation that percolates into the landfill and reduce leachate generation. By providing a barrier, geomembrane covers help contain LFG, preventing their escape into the atmosphere and facilitating their capture and use, thereby enhancing the overall environmental management of the landfill. Geomembrane covers may be paired with shallow gas collection directly under the geomembrane layer to minimize fugitive loss of gas.

Geomembrane covers represent a viable option for both interim and, with careful planning, final landfill coverage. Their ability to reduce leachate production, contain LFG, and provide stability on steep slopes makes them an effective choice in modern landfill management strategies. However, their long-term application as final covers require meticulous design to ensure durability and functional performance over time. Geomembrane covers may develop tears or punctures that can lead to the leakage of liquids or gases, compromising the landfill containment system. Such defects increase the risk of environmental contamination, making regular inspections and repairs essential for maintaining landfill integrity.

Regulation Changes

To further enhance LFG management and environmental protection, potential regulation changes could include incorporating the integration of a MOL in intermediate covers. This layer would consist of a highly permeable GDL, which could potentially be underlain by an optional vegetation layer. Such a configuration not only enhances gas collection efficiency but also facilitates the oxidation of methane.

The inclusion of this oxidation layer could make the intermediate cover more effective at reducing LFG emissions, aligning with the goals of RCRA. This potential change would help ensure that landfill design advancements continue to support environmental sustainability and compliance with federal standards. Emission measurements indicate that methane flux is smaller from final covers with non-defected alternative covers (e.g., exposed geomembrane cover) compared to conventional covers.

There have been many instances where intermediate covers are used for long periods of time—decades, in some cases. Potential regulation changes could include mandating the installation of final or enhanced cover once a landfill cell reaches its final grade or after a predetermined number of years to avoid long-term intermediate covers. This could be enforced by requiring landfill design plans to include a specified timeline for waste placement in each cell, along with a detailed schedule for installing the final cover once waste placement is complete. Similarly, regulation requirements could strengthen around the depth of intermediate covers to ensure proper methane mitigation.

Improving the enforceability of the monthly cover integrity program may also be a key consideration. Additional regulatory measures would be needed to ensure the ongoing maintenance and durability of landfill covers. Bare soils, in particular, are especially vulnerable to damage from precipitation, which can compromise cover effectiveness and increase the potential for emissions.

Implementation

The necessary technologies for enhancing intermediate and final landfill covers are readily available. The next step is to continue an ongoing dialogue about the potential for enhanced intermediate and final cover approaches and the practical aspects associated with these types of installations. Cover integrity monitoring could also help verify the ongoing effectiveness of these cover systems in real-world operational conditions.

Next Steps

As part of the white paper review process, EPA expects to hold an ongoing dialogue about the most effective approach to the installation of intermediate and final covers. This consultation could occur both through public comments on the white papers and during the Landfill Methane Technology Workshop in October 2024. The aim is to gather a wide range of insights and expertise to inform the development of the best possible design for these covers. A potential approach for the upcoming NSPS/EG rulemaking could be to work closely with stakeholders to develop best management practices that could be implemented to improve the application of intermediate and final covers in an effort to reduce emissions from MSW landfills.

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